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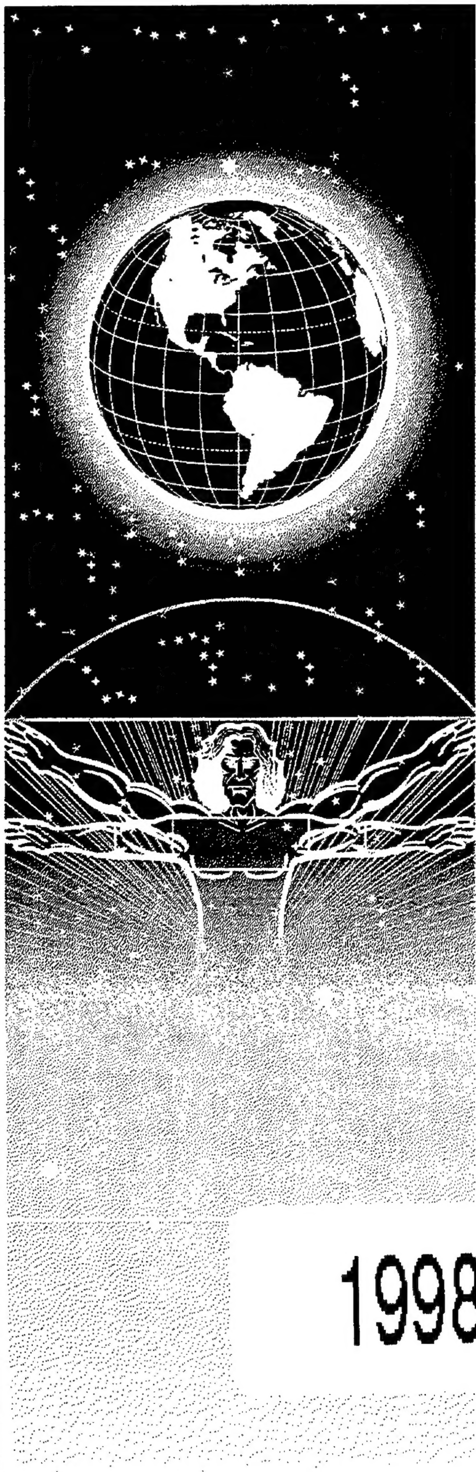

UNITED STATES AIR FORCE
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DYNAMICALLY ADAPTIVE INTERFACES: A PRELIMINARY INVESTIGATION (U)

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A "dynamically adaptive interface" (DAI) changes it's display or control characteristics based on behavioral or physiologic measures of the human operator in real time. The goal of a dynamically adaptive interface is to anticipate informational needs or desires of the operator and to provide that information without the requirement for an explicit control input. DAIs have the potential to improve overall human machine system performance if properly designed. This report documents an initial exploration of both theoretical and practical issues in dynamically adaptive interfaces. A DAI concept demonstrator was developed to assist in precision low-level navigation tasks. Advanced controls (a force reflecting stick) and displays (a flight director display) were incorporated into a dynamically adaptive interface concept demonstrator. A pilot study to evaluate the DAI was conducted. Three experimental conditions were evaluated: a baseline interface (conventional controls and displays), an advanced interface (advanced controls and displays), and an adaptive interface (dynamically alternating between baseline and advanced). The results indicated that there were significant performance advantages associated with both the advanced and adaptive interfaces relative to the baseline interface for tracking the optimal flight path.

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DYNAMICALLY ADAPTIVE INTERFACES: A PRELIMINARY INVESTIGATION

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Abstract

A "dynamically adaptive interface" (DAI) is a computer interface that changes the display or control characteristics of the system (perhaps both) in real time. The goal of dynamically adaptive interfaces is to anticipate informational needs or desires and to provide that information without the requirement for an explicit control input by the user. DAI's have the potential to improve overall human machine system performance if properly designed; they also have the very real potential to degrade performance if they are not properly designed. The fundamental challenge in designing effective DAI's is to provide dynamic changes in displays or controls that provide the right information at the right time. A collaborative research program to explore both theoretical and practical issues in dynamically adaptive interfaces has been initiated. A DAI concept demonstrator has been developed to assist in precision low level navigation tasks. Advanced controls (a force reflecting stick) and displays (a flight director display) have been incorporated into the dynamically adaptive interface concept demonstrator. The force reflecting stick uses the haptic perceptual channel to provide feedback with regard to the optimal flight path (thus, it is not only a control, but also a display). The visual display is a redesign of the Flight Director (FD) that provides a single configural format with all information relevant to the navigation task. A pilot study to evaluate the DAI was conducted. Three experimental conditions were evaluated: a baseline interface (conventional controls and displays), an advanced interface (advanced controls and displays), and an adaptive interface (dynamically alternating between baseline and advanced). The results indicate that there were significant performance advantages associated with both the advanced and adaptive interfaces relative to the baseline interface for tracking the optimal flight path. The baseline interface produced significantly better performance than the advanced interface for timing-related aspects of the navigation task. There were no significant differences between the advanced and the adaptive interfaces.

DYNAMICALLY ADAPTIVE INTERFACES: A PRELIMINARY INVESTIGATION

Kevin B. Bennett

Introduction

The overall goal for the design of complex sociotechnical systems is to maximize total human-machine system performance. Several characteristics of these systems (e.g., complexity, dynamics, consequences of accidents or sub-par performance) provide numerous challenges to achieving this goal. On the other hand, advances in computer science, engineering, human factors and related disciplines provide numerous resources that can be leveraged for effective design. A research program has been initiated to investigate an advanced interface design concept, the "dynamically adaptive interface" (DAI), in the domain of aviation. A DAI is an interface that changes the display or control characteristics of the system (perhaps both) in real time. Although the DAI concept may appear at first glance to be a radically new idea, we believe that it is simply an extension of useful and commonplace interface designs. Although the DAI concept may also appear to be a radical departure from traditional design wisdom ("consistency is the key to effective interface design"), we believe that DAI's will improve system performance if designed properly. The remainder of the introduction section will outline the DAI concept and related topics.

Sociotechnical systems are comprised of both human and machine components, and the allocation of tasks between these two components has been a traditional, long-standing concern for human factors. Initial guidelines for allocation consisted of lists of preferred activities that matched the perceived capabilities and limitations of each component; allocation was viewed as a discrete design decision with tasks being allocated in an all-or-none fashion. The term "automation" has historically been used to describe the most common form of allocation, where tasks performed by the human were reallocated to the computer. However, the meaning of the term automation has evolved through the years. In a recent discussion of automation Wickens (1992, p. 531) states that "Automation varies from that which totally replaces the human operator by computer or machine to computer-driven aids that help an overloaded operator." When viewed from this perspective it is readily apparent that other areas of research are very closely related to automation. For example, a primary focus in decision aiding is the provision of computerized decision support. To illustrate the overlap between automation and decision aiding consider the following quote by Rouse (1988, pp. 438-

439): "There are three general methods for aiding a user: (1) an aid can make a task easier, (2) an aid can perform part of a task, and (3) an aid can completely perform a task."

The relationship between automation and decision aiding can be made clearer by considering two alternative approaches to decision aiding. "Representation aiding" and "computational aiding" fall essentially at the endpoints of the continuum represented by Rouse's general methods. The representation aiding approach to decision support emphasizes the first two general methods (Bennett, 1992; Bennett & Flach, 1992; Bennett, Nagy, & Flach, In Press; Bennett, Toms, & Woods, 1993; Woods, 1991; Zachary, 1986). The task is made easier (Method 1) by presenting relevant system information in graphical formats, which allows an individual to use his/her powerful pattern-recognition capabilities. Although it is much more subtle, representation aids also perform part of the task for the user (Method 2). Properly designed configural displays will collect and integrate the subset of system data that is relevant to a particular issue and present that subset in the context of system goals. This is clearly a form of automation. To summarize, representation aiding seeks to capitalize upon, rather than to replace, natural human intelligence in the design of decision aids. The connection to automation is quite direct for computational aiding, where mathematical or artificial intelligence techniques (e.g., expert systems, neural networks, signal processing, queuing theory, nonlinear control) are used to provide a direct solution to a task or problem, thereby replacing the user (Method 3). For example, in summarizing their approach to decision support Berkan, Upadhyaya, Tsoukalas, Kisner, and Bywater (Berkan, Upadhyaya, Tsoukalas, Kisner, & Bywater, 1991, p. 8) state that "Operator tasks are emulated by building computer-based algorithms which validate sensor signals, strategies, commands, performance tracking, and which generate reliable decisions, and control actions."

The conceptual development and research literatures on automation and aiding have shown an historical parallel. Traditionally, decisions about both the allocation of tasks between human and machine (automation) and the type of support that was provided to assist the human in the completion of the allocated tasks (aiding) were made during the design phase and remained consistent during the operational phase. However, a great deal of recent interest has been shown in research efforts to develop "adaptive" automation and aiding, where the task allocation or decision support is changed in real time. For example, Hilburn, Parasuraman, & Mouloua (1995b, p. 347) have defined adaptive automation as the "...real-time allocation of functions between human operator and automated system..." Similarly,

Rouse (1988, p. 431) defines adaptive aiding as the "...human-machine design concept that involves using aiding/ automation only at those points in time when human performance in a system needs support to meet operational requirements -- in the absence of such needs, human performance remains unaided/manual, and thereby humans remain very much 'in the loop.'"

The present research investigates the concept of a dynamically adaptive interface, which cross-cuts the concepts of automation, aiding, and adaptation. The concept of an adaptive interface is not a novel concept. For example, many current software packages allow an individual to "personalize" their interfaces by choosing among options in a "preference" menu or window. The same general capability has been implemented in other applications, including advanced aircraft. Although these interfaces are adaptive in a certain sense, the adaptation does not occur in real time. Similarly, the concept of a dynamically adaptive interface is also not a novel concept. A simple example is found in many software packages today. Most applications incorporate pull-down menus that adapt dynamically as a function of a particular interactive sequence (e.g., menus that are updated dynamically to reflect the most recently accessed files or functions).

DAI's have the potential to improve overall performance of the human-machine system dramatically through an increased capability to provide the right information, in the right format, at the right time. The dominant theoretical perspective on human computer interface design describes effective interfaces as those which achieve "transparency" (Hutchins, Hollan, & Norman, 1986). That is, the interface effectively disappears, thus enabling the user to interact directly with the objects of interest in the domain, and to achieve effective interaction with a minimum of cognitive effort. Dynamically adaptive interfaces have the potential to take transparency one step farther. In traditional interfaces appropriate control inputs must be provided by the user when additional information is needed or desired; in dynamically adaptive interfaces this need or desire will be anticipated and the relevant information will be provided without the requirement for control input by the user. The potential benefits for complex dynamic domains are obvious. Operators must consider a great deal of information when completing domain tasks; at the same time, the amount of display "real estate" is often limited. The latter constraint is particularly evident in the domain of aviation (e.g., jet fighters) although the problem exists in other domains as well (e.g., process control). Because all information cannot be presented simultaneously, the operator must select the relevant subset. This requirement serves to increase

already high levels of workload and may occur at peak levels of workload (when the operator needs additional or different information to respond to domain challenges).

DAI's have the potential to improve overall human machine system performance by anticipating informational needs and providing that information in a timely fashion. However, the same characteristics of DAI's that enable these benefits also enable potential costs. Greenburg & Witten (1985, p. 31) summarize the concerns: "Although obvious advantages accrue... there are also obvious disadvantages to presenting users with a changing, adapting and perhaps apparently inconsistent interface." If designed improperly, DAI's have the potential to degrade system performance by preventing the development of automatic processes in the operator, by presenting irrelevant information, or in the worst case, by eliminating information that is currently needed. There is some empirical evidence supporting the benefits of dynamically adaptive interfaces. Greenburg & Witten (1985) developed a dynamically adaptive menu system for a telephone database system. They compared performance with this menu system to performance with a static menu system and found that "The results... support the use of adaptive user modeling. In the (admittedly highly constrained) example system, a computer interface can indeed adapt successfully to every user." It remains an open empirical question as to whether adaptive interfaces can be effective in domains that are not highly constrained. Critical issues include decisions about the choice of dynamic behaviors, about the information and knowledge that should be used to trigger these adaptive behaviors, and about the orchestration of these behaviors and information sources to facilitate performance.

Theoretical perspectives on dynamically adaptive interfaces

As the introduction suggests, a central component of dynamically adaptive displays is that they anticipate informational needs and adapt without explicit control inputs from the operator. Viewing DAI's from the perspective of automation allows us to benefit from the lessons that have been learned about automation through the years. Automation is often viewed (incorrectly) as a panacea for human error: by removing the human from the loop designers believe that the performance of the overall human machine system will be improved. Woods & Cook (1991, p. 1279) summarize what often happens instead: automation increases "... human workload at critical times, a condition called clumsy automation by Earl Wiener. Overall, technology centered automation appears to produce increments in workload and subtle decrements in practitioners' understanding of their environment. Significantly,

these deficits can create opportunities for human error that would not exist in less automated systems, producing a new class of failures."

From this perspective, the fundamental challenge in designing effective DAI's is to ensure that the dynamic changes are consistent with knowledge of the user (including current goals, workload, and levels of performance), knowledge of the task at hand, and knowledge of the current context (current system state and the inherent constraints associated with the domain). Another way of stating this is that dynamically adaptive interfaces should not be clumsy. As a form of automation they have the potential to create new types of errors and to degrade overall human machine system performance. For example, clumsy adaptation might not provide information that is relevant, or might take away information that is currently needed.

A theoretical approach referred to as "cognitive systems engineering" (CSE, Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994) can be applied to the practical problem of developing DAI's. The "cognitive system triad" (Woods & Roth, 1988) represents an assumption that the quality of performance in complex, dynamic domains is the result of three interactive and mutually constraining components (see Fig. 1): the cognitive demands produced by the domain of interest, the cognitive resources of the agent(s) that meet those demands, and the representation of the domain through which the agent experiences and interacts with the domain (the interface). From this perspective an adaptive interface must be able to recognize that a cognitive demand / cognitive resource mismatch has occurred (i.e., that the cognitive demands produced by the domain have exceeded the cognitive resources that the agent has available to meet them). After recognizing a demand/resource mismatch an adaptive interface must be able to determine the appropriate change in the amount or type of information that is required to alleviate the mismatch, and to adapt accordingly. The CSE approach, and the implications for the design of DAI's, will be considered further.

Cognitive Demands (Knowledge of domain)

Developing effective interfaces (especially dynamically adaptive interfaces) requires a deep understanding and explicit description of the "semantics" of a work domain. This requirement is even more important for developing dynamically adaptive interfaces. Rasmussen's abstraction hierarchy (Rasmussen, 1986; Rasmussen et al., 1994) is a theoretical framework for describing domain semantics in terms of a nested hierarchy of functional constraints (including goals, physical laws, regulations, organizational/structural constraints, equipment constraints, and

Conceptual Framework for Dynamically Adaptive Interfaces

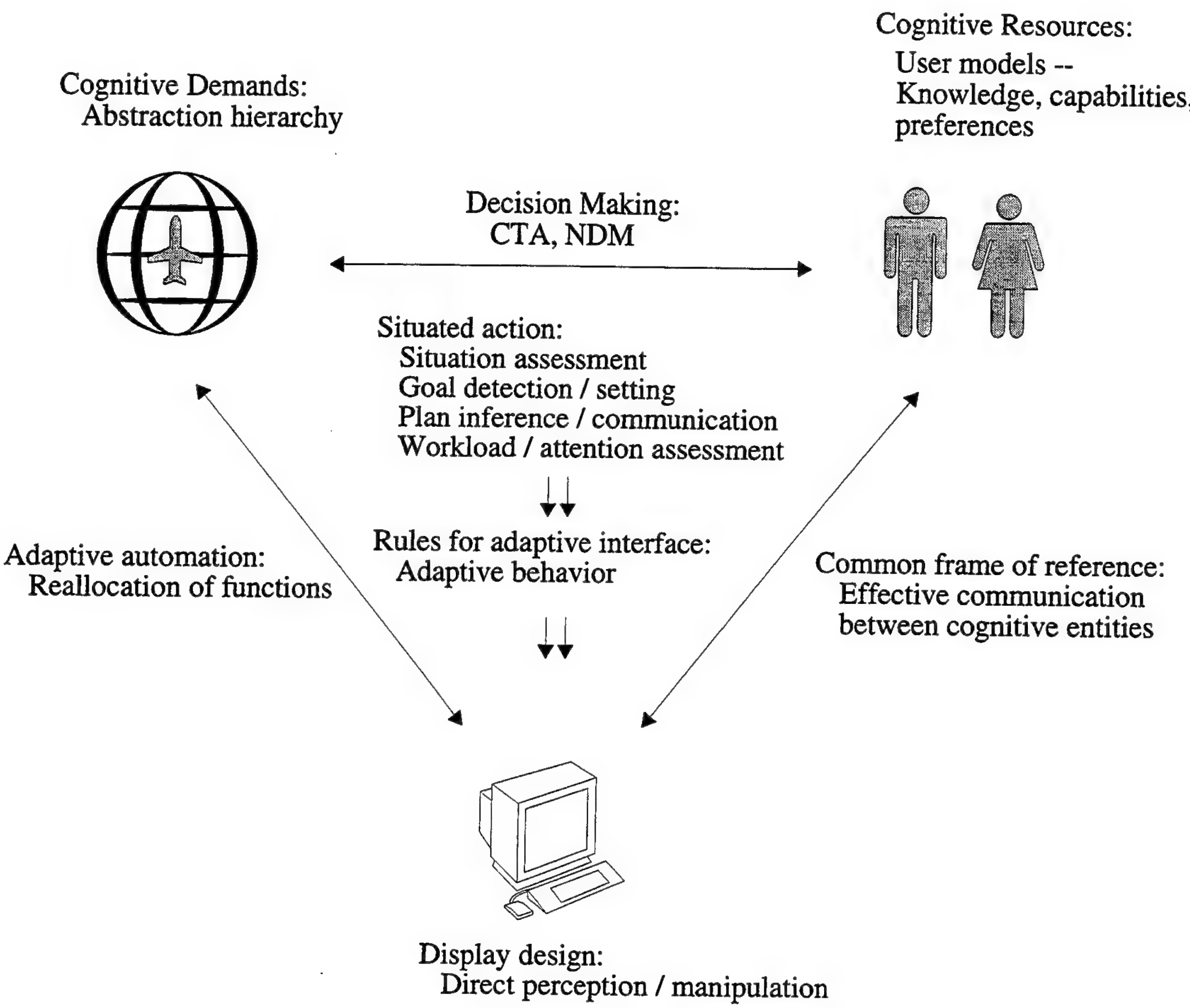


Figure 1.

temporal/spatial constraints). One way to think about the abstraction hierarchy is that it provides structured categories of information (i.e., the alternative conceptual perspectives) that an individual must consider in the course of accomplishing system goals. Thus, in complex domains, situation awareness requires the operator to understand the process at different levels of abstraction. Further, the operator must be able to understand constraints at one level of abstraction in terms of constraints at other levels.

Cognitive Resources (Knowledge of user)

Knowledge of decision making in domain. An abstraction hierarchy analysis provides a description of the domain constraints, independent of decision making in the domain. The design of effective adaptive interfaces will also require a complementary analysis of decision making within the constraints imposed by domain, including procedures, strategies, steps, subgoals, required information, and interrelations between procedures. Historically, decision research has focused on developing models that describe the generation of multiple alternatives (potentially all alternatives), the evaluation (ranking) of these alternatives, and the selection of the most appropriate alternative. By and large, perception was ignored. In contrast, recent developments in decision research, stimulated by research on naturalistic decision making (e.g., Klein, Orasanu, & Zsambok, 1993) has begun to give more consideration to the generation of alternatives in the context of dynamic demands for action. Experts are viewed as generating and evaluating a few "good" alternatives. The emphasis is on recognition (e.g., how is this problem similar, or dissimilar, to problems that I have encountered before?). As a result, perception plays a dominant role. This change in emphasis has increased awareness of perceptual processes and dynamic action constraints in decision making. These trends have, either directly or indirectly, led researchers in interface design to focus on the representation problem. Thus, the challenge for display design from this perspective is to provide appropriate representations that support humans in their problem solving endeavors.

Support for cognitive demand / cognitive resource mismatch: Interface design

Recently, a number of researchers have developed approaches to interface design that include an explicit consideration of the cognitive demands imposed by a work domain (i.e., explicitly recognize and support the human's role as a problem solver). Different terms have been used to describe these approaches, including direct perception (Moray, Lee, Vicente, Jones, & Rasumssen, 1994), ecological interface design (Rasmussen & Vicente, 1989), representational

design (Woods, 1991), or semantic mapping (Bennett & Flach, 1992; Bennett et al., In Press; Bennett et al., 1993). However, all these approaches share the same basic philosophical principles; collectively, they complement the principles of direct manipulation articulated by Hutchins, Hollan, and Norman (1986). There are two critical components of effective display design: correspondence and coherence.

Correspondence refers to the issue of content --- what information should be present in the interface in order to meet the cognitive demands of the work domain? Correspondence is defined neither by the domain itself, nor the interface itself: it is a property that arises from the interaction of the two. Thus, in Fig. 1 correspondence is represented by the labelled arrow that connects the domain and the interface. One convenient way to conceptualize correspondence is as the quality of the mapping between the interface and the work space, where these mappings can vary in terms of the degree of specificity (consistency, invariance, or correspondence).

Coherence refers to the mapping between the representation and the human perceiver. Here the focus is on the visual properties of the representation. What distinctions within the representation are discriminable to the human operator? How do the graphical elements fit together or coalesce within the representation? Is each element distinct or separable? Are the elements absorbed within an integral whole, thus losing their individual distinctness? Or do the elements combine to produce configural or global properties? Are some elements or properties of the representation more or less salient than other elements or properties? In general, coherence addresses the question of how the various elements within a representation compete for attentional and cognitive resources. Just as work domains can be characterized in terms of a nested hierarchy of constraints, so too, can complex visual representations be perceived as a hierarchy of nested structures, with local elements combining to produce more global patterns or symmetries.

Whether a display will be effective or not is be determined by both correspondence and coherence. More specifically, the effectiveness of a display is determined by the quality of the mapping between the constraints that exist in the domain and the geometrical constraints that exist in the display. The display constraints are defined by the spatio-temporal structure (the visual appearance of the display over time) that results from the particular representation chosen. In configural representations the geometrical display constraints will generally take the form of symmetries --- equality (e.g., length, angle, area), parallel lines, colinearity, or reflection. The core problem in implementing effective displays is to provide visual representations that are perceived as accurate reflections of the abstract domain

constraints: Are the critical domain constraints appropriately reflected in the geometrical constraints in the display? Are breaks in the domain constraints (e.g., abnormal or emergency conditions) reflected by breaks in the geometrical constraints (e.g., emergent features such as non-equality, non-parallelism, non-closure, bad form)? Only when this occurs will the cognitive agent be able to obtain meaning about the underlying domain in an effective fashion.

Situated action. The quality of the interface is especially important in coordinating intelligent machine and human activities. Researchers have investigated this facet of the interface problem in the context of systems that have a machine expert system (e.g., Roth, Bennett, & Woods, 1987; Suchman, 1987). Two central principles have emerged: "situated action" and "mutual intelligibility" (which depends upon a "common frame of reference"). Suchman (1987) has proposed that human-human communication provides a particularly relevant analogy to frame questions of human computer interaction. She contrasts the traditional view of intelligent action (the development and implementation of plans) to situated action, stating that "... purposeful actions are inevitably *situated actions*. By situated actions I mean simply actions taken in the context of particular, concrete circumstances" (p. viii). Suchman (1987) applies this view of intelligent action to the design of human computer systems, and observes that "Interaction between people and machines implies mutual intelligibility, or shared understanding" (p. 6). Roth, Bennett, and Woods (1987) reached similar conclusions in their evaluation of an expert system designed to assist technicians in the repair of an electro-mechanical device. The design of the system interface was "opaque" and therefore inhibited the development of a mutual understanding between the human and machine experts. As a result the two cognitive entities worked independently and in parallel (rather than orchestrating their activities), and overall system performance was degraded significantly.

Dynamic adaptations

All of these considerations come together when considering dynamic adaptive behaviors on the part of the interface. One basis for adaptive changes has been referred to as "human performance models" (Rouse, 1988). The goal of these models is to predict when degradations in performance are likely to occur, which serves as a basis for changing the level of aiding. Models could be devised to represent many aspects of human performance, capabilities and limitations, including 1) knowledge of the system (e.g., capabilities, limitations, tendencies that are specific to the interface and its adaptive behaviors), 2) knowledge of the task domain (e.g., declarative or procedural knowledge), or

3) other information (e.g., processing capabilities, interaction style, preferences, strategies). Rouse (1988, p. 434) summarizes the role that human performance models may play: "Thus models are needed whereby on-line predictions of performance can be obtained based on the current state of task demands and the availability of human sensori-motor and information-processing resources. These models represent one of the ways in which expertise about human behavior and performance can be embedded in an intelligent support system."

Human performance models of mental workload would be particularly useful in this context. It is a fairly well established fact that the relationship between workload and performance is not necessarily a linear one. More specifically, equal increases or decreases in workload are not reflected by equal increments or decrements in performance. As workload increases from a low to a high level individuals are often able to mobilize resources to meet the increased demand, and performance may not suffer. However, as an individual approaches the maximum level of workload small increases may have precipitous (and negative) effects on performance (e.g., the "straw that broke the camel's back"). From the perspective of dynamically adaptive interfaces, on-line psychophysiological measurements of workload might be useful through the provision of information that could be used to improve the timing of adaptive interface changes, and therefore overall performance.

Rouse (1988, p. 435) refers to "on-line assessment" as a second category of techniques that could be used to trigger changes in the interface: "Beyond predicting human performance and anticipating degradations, adaptive aiding requires on-line assessments of what the human is doing and, if possible, what the human intends to do..." An obvious example of on-line assessment is the levels of performance that are being maintained. If performance is showing trends of degradation then adaptive measures could be considered. A version of on-line assessment that Rouse believes to have particular promise is a category that he refers to as "leading indicators." Leading indicators are secondary performance measures which exhibit performance decrements in advance of primary performance indicators (and therefore would be quite useful in triggering adaptive changes). On-line assessment can also refer to the assessment of user intent: "It was recognized quite early... that knowledge of humans' intentions was necessary if adaptive aiding was to succeed fully." (Rouse, 1988, p. 435). The attempts to develop intelligent tutoring systems (e.g., Polson & Richardson, 1988) have demonstrated unequivocally that to do so represents a formidable challenge.

Summary

The preceding theoretical perspective, and the analyses that it suggests, forms the basis for the development of dynamically adaptive interfaces. The abstraction hierarchy analysis reveals the critical domain constraints (the cognitive demands that must be met, and the domain resources that are available to meet them). The cognitive task analysis defines the decisions that need to be made to meet domain goals, and the information that is relevant to those decisions. This information is used, in conjunction with the semantic mapping principles of display design, to develop displays that appropriately reflect domain constraints and thereby assist in decision making and problem solving. These analyses also provide knowledge about situated action, and constitute the basis for dynamically adaptive behaviors on the part of the interface. Applying these analyses will result in a definition of what adaptations are appropriate in the interface, and the development of rules / models that describe when those adaptations should occur. These rules / models include knowledge of the operator's performance, the operator's workload, general aspects of the task/domain, and specific aspects of current system state (i.e., an assessment and continuous monitoring of the domain for changes that have implications for goals and required actions -- the context or situation). The end result will be a common frame of reference, or mutual intelligibility, between the human and the adaptive interface. Dynamic alterations in the interface will be consistent with current goals and context; the intelligent action on the part of the interface will improve overall human-machine system performance.

Concept demonstrator

A concept demonstrator was developed to investigate issues in the design of dynamically adaptive interfaces for a class of aviation tasks -- precision low level navigation. A characteristic of these tasks is the requirement to fly an aircraft along a predetermined path (or, at a minimum, to intersect predetermined waypoints) and to be at a specific point in the flight path at a specific time. One example of a low level navigation task is to deliver ordnance in enemy territory. To accomplish this task a pilot may be required to fly along a particular path (to avoid ground based threats), and to arrive at waypoints or the target site at a particular point in time (to benefit from air cover that has been provided to mask arrival, or to coordinate with other offensive activities). An advanced control (a force reflecting stick) and an advanced display (a flight director display) were developed to support pilots in these tasks. The force reflecting stick provides changes in resistance to a pilot's control input (or the amount of force that is required to implement the control input) that varies as a function of the airplane's deviation from the optimal flight path. The flight director display

integrates several pieces of navigation-related information (e.g., altitude, line-up information, airspeed) in a single "configural" display that provides a commanded steering input to the pilot. The advanced controls and displays will be described in greater detail.

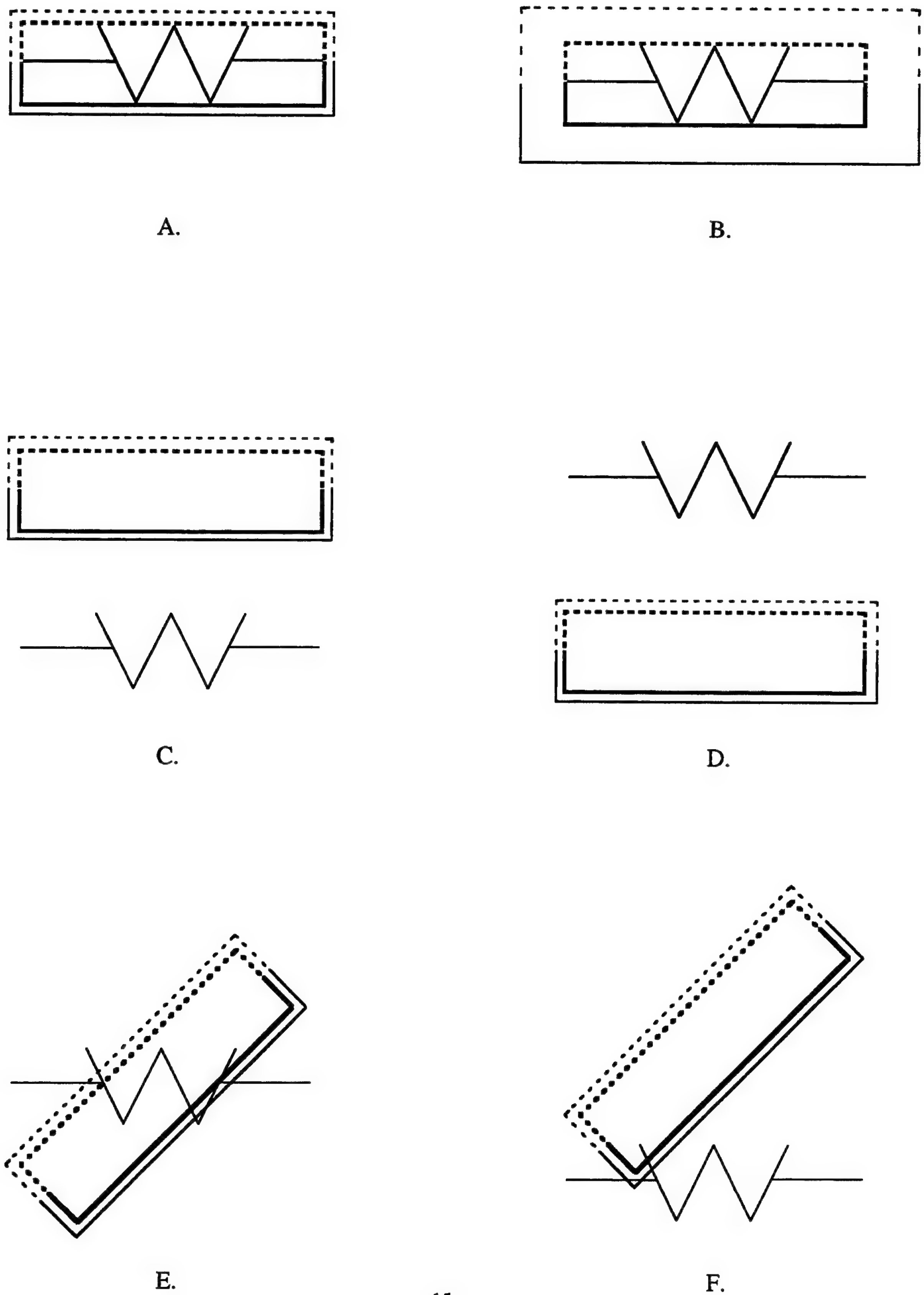
Advanced display: Configural flight director HUD

The configural flight director (CFD) HUD display combines aspects of both representational and computational aiding. The computational aiding component of this display should be considered as a subtle form of automation. Consider the following quote by Rouse (1981, p. 75): "... consider an aircraft flight director, where the computer integrates a variety of sources of information, referenced to a desired flight path and profile, and displays a 'command' telling the pilot what to do (i.e., keep the aircraft symbol lined up with the cross hairs). One can easily argue that the computer is controlling through the pilot in the sense that it is directing the pilot's actions (hence the term flight director). Certainly the pilot is not 'closing the loop' in the usual sense that an automobile driver does." The algorithms that underlie this form of calculational aiding are described in Appendix A.

The representation aiding component of consists of two rectangular boxes (see Fig. 2a) and a visual reference point (the watermark symbol). The visual reference point remains in a fixed position in the HUD and both rectangles move dynamically to signify deviations from the recommended flight path. Both rectangles have a dashed and a solid component. The solid component serves as a reference to ground, while the dashed component serves as a reference to the sky. This aspect of the display serves as a cue for the aircraft-ground relationship: when the plane is right side up the solid portion will appear on the bottom, when the plane is upside down the solid portion will appear on the top.

Deviations of the aircraft from the flight path resulted in movements of the configural display from a fixed reference at the center (waterline). Changes in the location and orientation of these two rectangles (relative to the fixed visual reference point) provide "emergent features" that signify commanded roll and pitch inputs to the pilot. If the values of all variables are consistent with the optimal flight path then the rectangles will enclose the watermark symbol and will be centered and aligned with it (see Fig. 2a). A deviation in altitude (pitch) is represented by a vertical displacement of the rectangles. When the rectangles are above the watermark the airplane is below the recommended flight path (see Fig. 2c); when the rectangles are below the watermark the plane is above the recommended flight path (see Fig. 2d). A deviation in heading is represented by rotation of the rectangles. When the airplane's course is to the

Figure 2



left of the recommended flight path the rectangles will rotated clockwise, relative to the watermark (see Fig. 2e), and vice-versa. A lateral and vertical deviation from the flight path is in Fig. 2f. This figure represents a commanded input to turn the plane to the left and to simultaneously increase altitude. Thus, the display was designed to be a "fly-to" type of display in which the pilot attempts to match the roll and pitch suggested by the rectangles, thereby keeping the waterline within the rectangles and the aircraft on the desired flight path.

Airspeed. The two rectangles represent actual and commanded airspeed. The bold rectangle provides a visual representation of the airspeed goal; the non-bold rectangle provides a visual representation of current airspeed with respect to this goal. When current airspeed is greater than the goal airspeed the non-bold rectangle will be smaller than the bold rectangle (see Fig. 2b); when current airspeed is less than the goal airspeed the non-bold rectangle will be larger than the bold rectangle. When considered together, the two rectangles provide an "emergent visual feature" that specifies both the goal for airspeed and the degree of deviation from this goal directly.

It is important to note that the bold rectangle represents the goal airspeed (which can change, even though the size of the rectangle does not) and that the bold rectangle represents the deviation between actual and commanded airspeed, not current airspeed. For illustrative purposes, imagine that a pilot is maintaining a constant airspeed while navigating towards a waypoint. Further imagine that this constant airspeed is less than the airspeed required to place the aircraft at the waypoint at the appropriate time. In this scenario the distance between the plane and the waypoint is decreasing at a constant rate, but the time error is constant.

Advanced control. Brickman, Hettinger, Roe, Lu, Repperger, and Haas (In Press) developed a force-reflecting, haptically-augmented aircraft control stick and evaluated it in the context of an instrument landing task. When the ground surface is obstructed (e.g., when flying through low clouds), a pilot relies upon instruments that provide information with respect to an optimal approach path to the runway (in particular, glideslope and line-up information). The force reflection stick represents an augmentation of existing instrumentation. In contrast to a conventional stick, the augmented stick serves as both a control and a display. For example, if the plane deviated to the right of the optimal approach path the pilot would experience an increase in resistance when attempting control inputs to the right, and a decrease in resistance when attempting control inputs to the left. Thus, the force reflecting stick is not only a control, but also a display which uses the haptic channel to provide feedback with regard to the optimal approach path.

Dynamically adaptive interface: Preliminary evaluation

The concept demonstrator was used to perform a preliminary investigation of dynamic adaptive interfaces. Three different interface conditions constituted the primary independent variable of the experiment; each will be described in greater detail.

Baseline interface. The baseline interface contained typical controls and displays and was fairly representative of current fighter HUDs in the "declutter mode" (see Fig. 3a). A heading scale was positioned near the bottom of the display, and airspeed (KCAS) and barometric altitude tapes were arranged vertically on the left and right sides of the HUD, respectively. A horizon bar and flight path marker (FPM) were also provided, however, no pitch and dive scale was depicted. Digital readouts of instantaneous load factor (G) and angle of attack (degrees) were presented on the left side above the airspeed scale. Waypoint information was presented in the format "__ D__" (read as __nautical miles from waypoint number __) on the lower right of the HUD, next to the heading scale. Two sets of carets were presented on each of the three tapes. One set of carets depicted the current values for heading, altitude, and airspeed. The second set of carets depicted the desired or "commanded" values for each of these variables. For heading and altitude these commanded values are the corresponding information with regard to the next way point; for airspeed it is an estimated time of arrival (see method section for additional details).

Advanced interface. The advanced interface contained the CFD HUD and the force-reflective stick described previously. The calculational aiding component consists of the algorithms lying behind the flight director and force-reflective stick. As opposed to the baseline interface (which presents current values for task-relevant variables), the advanced interface calculates commanded control input(s) to the pilot that minimize spatial and temporal errors relative to the optimal flight path. The representational aiding component of the advanced interface consists of multi-modal, configural representations of this information. The combined haptic-visual displays suggest the appropriate control input through coherent representations that integrate all of the relevant variables (consistent with the principle of "correspondence") in a centralized and easily interpretable format (consistent with the principle of "coherence").

Adaptive interface. The adaptive interface consisted of both the advanced and the baseline interfaces. The primary source of information that was used as a basis for the dynamic adaptation of the interface was the on-line assessment of performance. The aircraft's spatial position relative to the pre-planned flight path and its temporal position relative

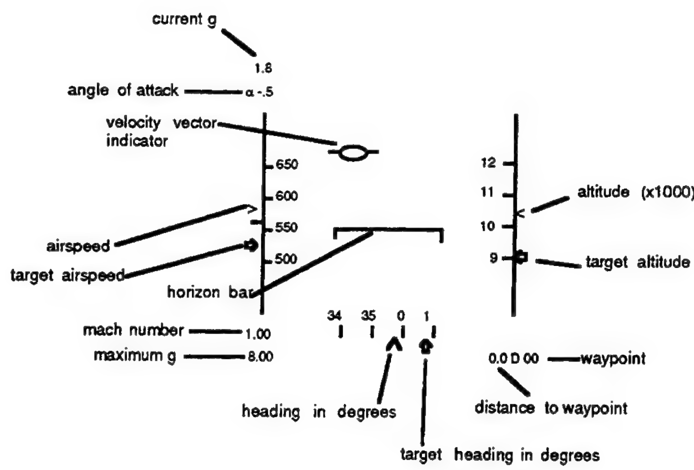


Figure 3a. Baseline HUD

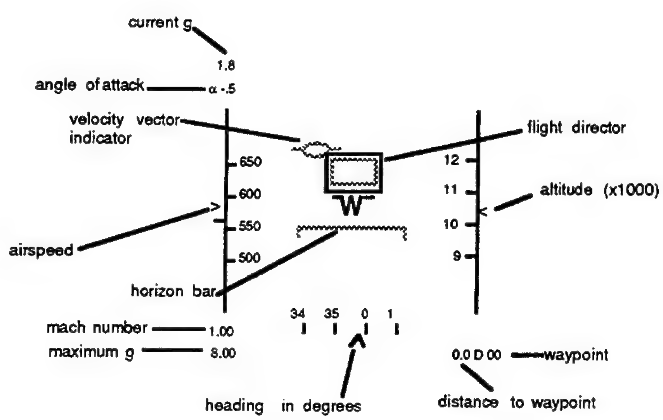


Figure 3b. CFD HUD

to the timing goals were monitored constantly, and the degree of deviation served as the basis for dynamic adaptation (switching between the two interfaces). When performance was within spatial and temporal performance boundaries the baseline interface was present; when these boundaries were violated the advanced interface became present (the visual aspects of the baseline interface were still present in the HUD, but dimmed). Spatial and temporal "dead-bands" were implemented to ensure that interface "hysteresis" (rapid alternation between the two interfaces) did not occur.

Two air force pilots completed a precision, low-level navigation task. Pilots completed this mission under six experimental conditions: three different interfaces (baseline, advanced, adaptive) in combination with two levels of turbulence (present / not present). Performance was evaluated on several dependent measures, including spatial deviation from the optimal flight path (horizontal and vertical), temporal deviation from timing goals, and subjective measures of workload.

Method

Subjects. Two experienced US Air Force pilots served as subjects. Subject A was 31 years of age and had in excess of 2300 hours of flight experience. Subject B was 55 years of age and had over 3200 hours of flight experience. Both subjects had normal or corrected-to-normal vision.

Apparatus. The experiment was conducted in the SIRE facility's Fusion Interfaces for Tactical Environments (FITE) laboratory. The simulated F-16 cockpit (fiberglass body) contained six Liquid Crystal Display (LCD) head-down displays (only one LCD was used, and only to provide feedback), an F-16C throttle and sidestick controller (connected to a McFadden hydraulic control loader). The cockpit was located in the center of a cubic (8' x 8' x 8') projection room; visual scenes were produced by four Apollo color projectors, driven by two Intergraph TDZ-310 graphics workstations running Windows NT. The workstations had Realism Z-13 graphics accelerator boards, using graphics generated with the OpenGVS Application Programming Interface (API). The output to each projector was 32-bit color on a 1024x768 pixel display.

Stimuli. An out-the-window (OTW) display of simulated terrain was presented on the inside of the projection room. Each HUD was incorporated into the OTW display, at a fixed location directly in front of the cockpit, occupying approximately a 20-degree field of view. There were three interface conditions: baseline, advanced, and adaptive.

The baseline interface is illustrated in Figure 3a. The commanded heading was the straight-line heading to next waypoint. The commanded altitude was 300 feet throughout the majority of the flight, but changed to 1000 feet at the end of a trial. The commanded airspeed consisted of an estimated time of arrival (ETA) at the upcoming waypoint, assuming a direct path and a constant speed. The equation was $ETA = t + d / v$, where "t" is the current time in seconds, "d" is the distance in feet to the upcoming waypoint, and "v" is the current aircraft ground speed (horizontal velocity component) in feet-per-second. At each update, the ETA was computed and compared to the waypoint's target arrival time (determined in advance). If the ETA was sooner than the target time, the commanded airspeed directed the pilot to slow down; if the target time was sooner than the ETA, the pilot was directed to speed up. The maximum directed change was 100 knots, which occurred if the subject was 45 seconds or more off schedule, and timing errors were mapped linearly to directed airspeed changes.

The advanced interface contained an advanced control (force-reflective, haptic stick) and an advanced display (a configural flight-director HUD -- CFD HUD). The CFD HUD used both computational and representational aiding. The representational aiding was provided by the analog configural display, as discussed previously (see Fig. 2 and the related discussion). The computational aiding component was provided by "flight director" algorithms that provided command inputs: the CFD HUD represented the roll, pitch and throttle inputs that were necessary for maintaining the aircraft's position on the pre-planned flight path, rather than the direct representation of those parameters. The algorithms included "centerline recovery mode", with "turn short mode" for primary waypoint sequencing and the "90-degree test" for backup waypoint sequencing. The navigation calculations resulted in a directed bank and pitch angle for the pilot, which was then displayed graphically in the HUD via the Flight Director, after being filtered using a simple "delta-limit filter" to prevent abrupt changes in the display. The details of these algorithms are provided in Appendix A. The CFD HUD also used the commanded airspeed calculations employed in the baseline interface.

The advanced interface condition also contained a force-reflective haptic stick. The sidestick controller was connected to a McFadden hydraulic control loader, which allowed numerous aspects of stick feel to be modified in real-time. The force-reflective stick was also programmed to provide a command input: a pilot who initiated inappropriate control inputs (those which would move the aircraft away from the optimal flight path) would receive haptic feedback in the form of increased resistance. The amount of resistance depended upon the amount of deviation from the optimal flight

path, both horizontal and vertically (resistance was proportional to the cube of the positional error). For example, if the subject's altitude was below the target flight path, more force was required to push the stick forward (pitch down); if the subject's altitude was too high, more force was required to pull the stick back (pitch up). Similarly, if the subject was left of the flight path, the stick was harder to push left, and if the subject was to the right, the stick was harder to push right. No force was ever required to keep the stick centered.

In the adaptive interface the baseline interface was present when the aircraft was within performance boundaries (spatial deviations from the optimal flight path of less than 500 feet laterally or 50 feet vertically; timing deviations between the ETA and timing goal of less than 10 seconds). The advanced interface was present when the aircraft was outside these performance boundaries (the visual components of the baseline interface remained in the HUD, but were dimmed). To prevent interface "hysteresis" (rapid switching between interfaces) deadbands were implemented. After an interface exchange had occurred, a return to the previous interface could only transpire when the performance boundary was exceeded by an additional 10 feet (e.g., a 40 feet vertical deviation would trigger a return to the baseline interface) or when the performance boundary was exceeded by less than 10 feet but was maintained for more than 10 seconds (e.g., a 45 feet vertical deviation maintained for 10 seconds would trigger a return to the baseline interface).

Simulated wind turbulence could be present in some experimental trials. The turbulence model consisted of a sum of seven sinusoids, attenuated with a high-pass filter to emphasize disturbances in the lower frequencies. The turbulence model used the following sum of sinusoids ("t" is time in seconds): $F(t) = 0.99 \sin(0.2512\,t + 3.0) + 0.95 \sin(2.1352\,t + 11.0) + 0.93 \sin(3.8936\,t + 19.0) + 0.85 \sin(5.4008\,t + 31.0) + 0.75 \sin(6.6568\,t + 37.0) + 0.68 \sin(8.4152\,t + 41.0) + 0.59 \sin(9.9224\,t + 47.0)$. The turbulence was applied separately to the x-, y-, and z-components of the aircraft's velocity, resulting in a seemingly random three-dimensional wind velocity.

<u>Procedure</u>. Each subject participated in one training session and three experimental sessions, with each session lasting about 90 minutes. Training consisted of a briefing on the experimental task and procedures, instructions describing the use of each of HUDs and cockpit controls, a subsequent question and answer period regarding the use of HUDs, and several minutes of unconstrained flight in the simulated environment. During both training and experimental sessions subjects completed 6 blocks of trials. These 6 blocks of trials resulted from the factorial combination of the 3 interface conditions (baseline, advanced, or adaptive) with the 2 turbulence conditions (turbulence or no turbulence).

The presentation order of blocks was randomized. In the training session subjects completed 2 trials within a block; in the experimental sessions subjects completed 3 trials within a block.

Pilots were informed of their display and turbulence condition prior to each block. Each trial began with the simulated aircraft flying at an airspeed of 450 knots with a heading of 5 degrees and an altitude of 300 feet above ground level altitude (AGL). Pilots were instructed to maintain their flight path and approach the first waypoint which was 6 nautical miles away. Pilots were told to proceed past the first waypoint to a second waypoint 6 nautical miles beyond the first. Upon reaching the second waypoint, pilots had to change their heading to 55 degrees and begin an approach to the next waypoint, also 6 nautical miles away. After reaching the third and final waypoint, pilots were instructed to change their heading to 100 degrees and proceed toward a runway. On the approach to the runway, pilots were required to increase their altitude to 1000 feet in preparation for a weapons delivery. The trial was completed when the simulated aircraft passed over the front edge of the runway. Each trial was approximately three and one-half minutes in length. After each trial subjects were provided feedback (RMS error values for lateral and vertical deviations from the prescribed flight path; RMS error for temporal deviations from waypoint timing goals). Upon completing each block of trials, subjects were asked to assess their workload for that particular condition using a multidimensional self-report of workload (NASA TLX -- Hart and Staveland, 1988).

Results

Analyses were performed for four dependent measures (horizontal error, vertical error, timing error, and workload assessments). A 3 (display) x 2 (turbulence) x 3 (day) repeated-measures, within-subjects ANOVA was performed on each dependent measure; post-hoc analyses (the Tukey Honest Significant Difference test) was conducted on significant effects. RMS error provides a single, summarized estimate of performance within a trial and RMS error scores were conducted for horizontal error, vertical error, and timing error. Horizontal and vertical errors were calculated by comparing the optimal flight path to the actual flight path. Ten data samples were taken for each second of flight time. The formula for RMS error is $\sqrt{\Sigma(F-X)^2/(n-1)}$, where X is the value of the horizontal or vertical position of the aircraft during a sample, F is the horizontal or vertical position of the optimal flight path, and n is the number of samples. An average RMS score for a block of trials was computed by averaging the three trials within that block. For horizontal error the interaction effects between display and day, $F\,(4,4) = 9.13$, $p < 0.03$, and display, day,

and turbulence, $F(4,4) = 15.26$, $p < 0.02$, were significant. The means for the three-way interaction effect are illustrated in Fig. 4a. The post-hoc analysis for this effect indicated that no comparisons between the advanced interface and the adaptive interface were significant. With no turbulence both the adaptive and advanced interface produced significantly better performance than the baseline interface in the first experimental session; the advanced interface produced significantly better performance than the baseline interface in the second session; there were no significant differences in the third experimental session. With turbulence present both the adaptive and the advanced interfaces produced significantly better performance in all three experimental sessions. For vertical error the interaction effect between display and day, $F(4,4) = 10.70$, $p < 0.03$ was significant. The means for this effect are illustrated in Fig. 4b. Again, the post-hoc analysis revealed that no comparisons between the advanced interface and the adaptive interface were significant. Both the adaptive and advanced interface produced significantly better performance than the baseline interface in the first experimental session; the advanced interface produced significantly better performance than the baseline interface in the second and third sessions. An RMS timing error score was also calculated (substituting an optimal flight time for the optimal flight path in the RMS formula listed above). The main effect of display was significant, $F(2,2) = 19.59$, $p < 0.05$. The post hoc analysis revealed that the baseline interface produced significantly better timing performance than the advanced interface. For illustrative purposes the display by day interaction effect means are illustrated in Fig. 4c. An overall estimate of subjective workload for each block of trials was obtained by averaging across the six subscale ratings of the NASA TLX. The ANOVA revealed no significant effects; the means for the three-way interaction are illustrated in Fig. 4d.

General discussion

Due to the low number of subjects, and the limited evaluation performed, the results must be interpreted with caution. The results appear to indicate that the decision support (a combination of representational and calculational aiding) provided by the advanced controls and displays was generally successful in improving performance at the low-level precision navigation task. Both horizontal and vertical tracking measures revealed significant improvements in performance when these controls and displays were present, relative to the baseline interface. The best tracking performance was associated with the advanced interface (controls and displays always present): all statistical comparisons with the baseline interface were significant, with the exception of the horizontal error on Day 3 with no

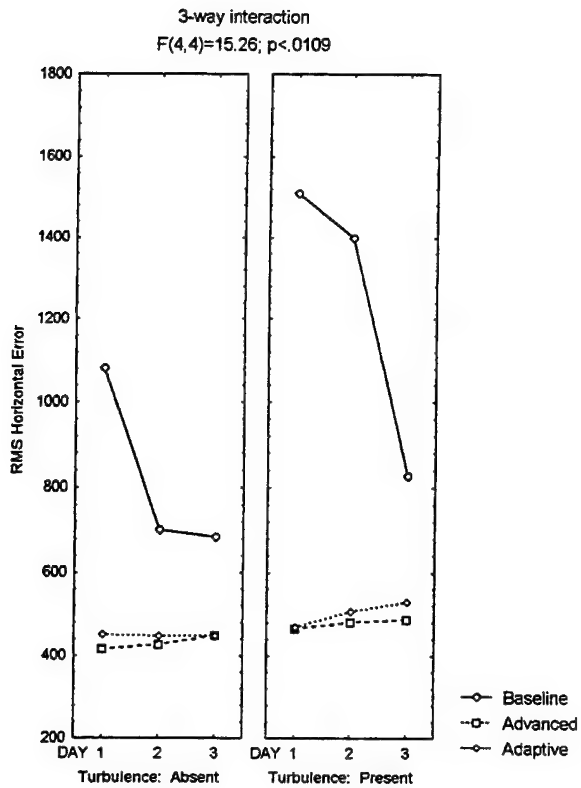


Figure 4a

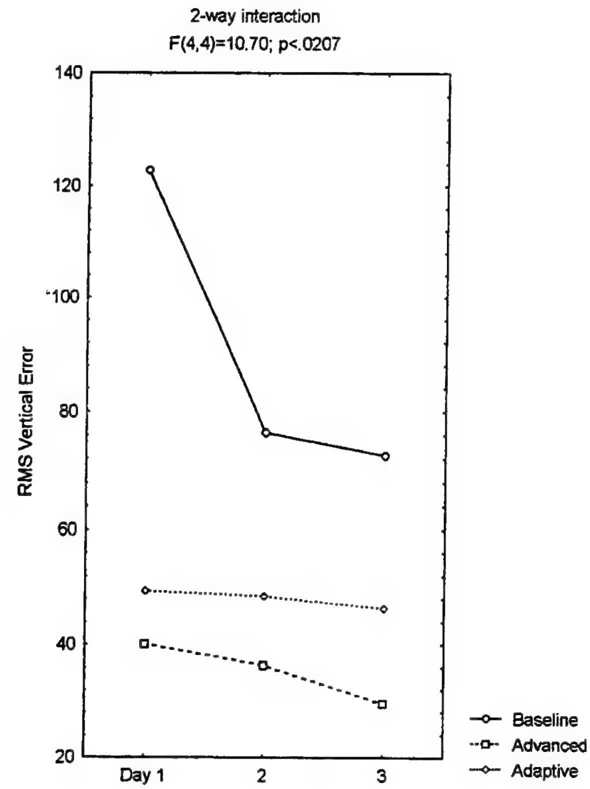


Figure 4b

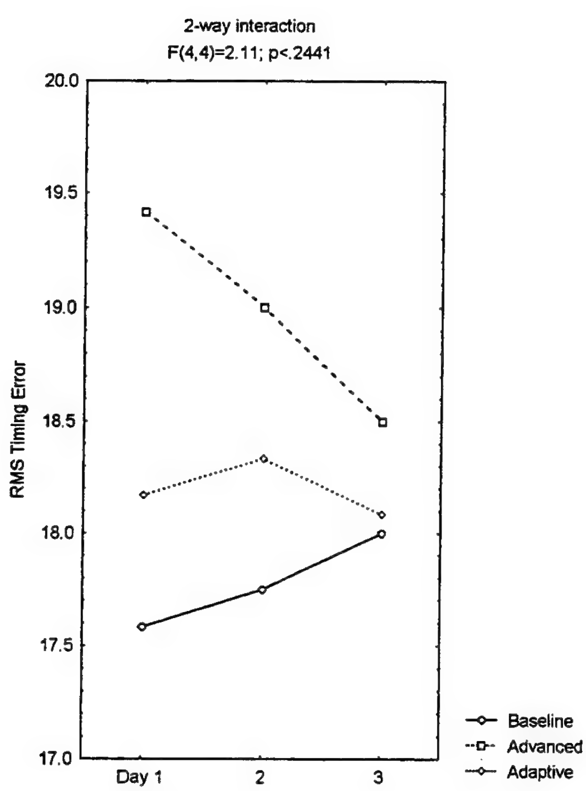


Figure 4c

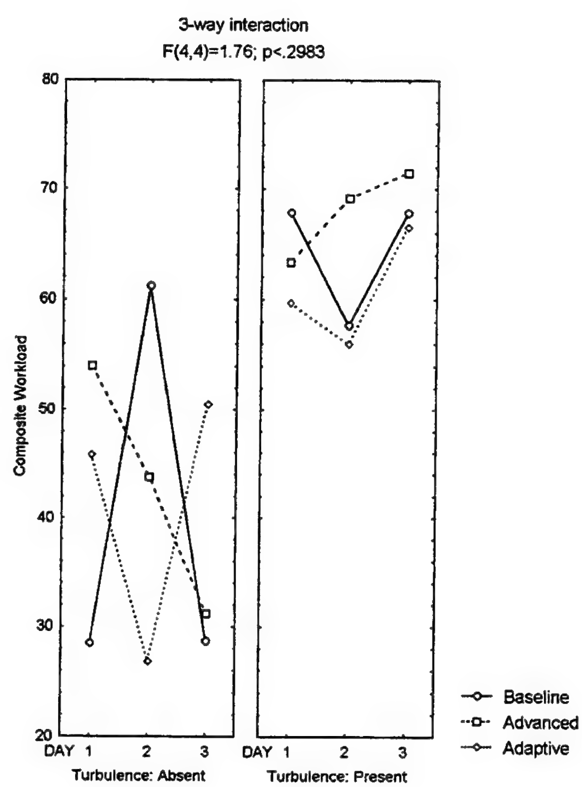


Figure 4d

turbulence present. The adaptive interface (dynamic adaptation between advanced and baseline interface) produced consistently better tracking performance than the baseline interface. For both horizontal (turbulence and no turbulence) and vertical RMS error the adaptive interface produced significantly better performance on Day 1. These performance advantages remained significant across Days 2 and 3 for horizontal error when turbulence was present; for horizontal error without turbulence and for vertical error the significance of the performance advantages disappeared with experience at the task.

Given the limitations of the pilot study, these results provide a strong validation of the utility of the advanced control and display in supporting the pilots in a critical aspect of precision, low-level navigation: following a pre-determined flight path. These results were obtained despite the fact that several factors worked against these controls and displays: only two pilots participated in the experiment, they were much more familiar with the traditional interface, and the six hours of experience with the advanced controls and displays represents a very short learning period.

In contrast to tracking error, the advanced controls and displays did not appear to support the pilots' efforts to meet the timing goals of the low-level navigation task. The advanced interface produced significant decrements in RMS timing error relative to the baseline interface; the adaptive interface produced worse performance than the baseline interface, although the differences were not significant. Consideration of timing performance across display and day yields some interesting insights (see Fig. 4c). Performance was always best for the baseline interface. However, by the third experimental session the difference between the baseline and the adaptive interfaces was negligible. In contrast, performance for the advanced display was extremely poor at the outset of the experiment, but improved steadily with experience at the task.

Because all three interfaces used the exact same algorithm to produce commanded and actual airspeed, the difference must lie in issues of representation. There are at least two potential explanations for this decrement. The first is relatively simple, and is related to perceptual salience: it was difficult to make the two configural rectangles sufficiently discriminable with the lighting and projection hardware configuration that was used. Increasing the difference in perceptual salience between the commanded and actual rectangles may produce better results. An alternative explanation is related to the quality of the basic perceptual judgments that the two representations required the pilots to make. The baseline interface required pilots to make a judgment of the differences in vertical extent

between two symbols (the carets representing actual and commanded airspeed) that shared a common baseline. In contrast, the advanced interface (and the adaptive interface when the advanced HUD was present) required pilots to compare the relationship between two rectangles (either size, area, or the space between sides) that were changing in both location and orientation. These results are consistent with the findings of Cleveland and his colleagues (e.g., Cleveland, 1985) and suggest that the most likely explanation of the significant performance decrements in RMS timing error with the advanced HUD is related to the difficulty of the perceptual judgments that it required (relative to the baseline). A redesign of the representation of timing information should be considered; these modifications would be fairly simple.

In terms of the overall goal of the proposed research program -- to investigate theoretical and practical issues in the development of dynamically adaptive interfaces -- the critical comparisons in performance were between the advanced and the adaptive interfaces. Differences in performance between these two interfaces were negligible for horizontal error. For vertical error the differences were small, but consistent, and favored the advanced interface. However, for both these dependent measures no direct comparisons were significant (or even approached significance). The differences in timing error were more pronounced, and favored the adaptive interface.

These results represent an encouraging pattern of results. One of the primary concerns with the concept of a dynamically adaptive interface is based on the potential for a "changing, adapting and perhaps apparently inconsistent interface." (Greenberg & Witten, 1985, p. 31). Both practical guidelines and theoretical approaches to interface design identify consistency as a fundamental component of effective design. This conclusion is a very reasonable one, as evidenced by both common sense and experimental research. When individuals are presented with consistent information they are typically able to develop extremely effective patterns of behavior over time, behavior that is characterized by the parallel and automatic processing of both external information and overt responses. With some nuances to differentiate between terms, researchers have labelled this type of behavior as "automatic processing" (e.g., Shiffrin & Schneider, 1977), "skill-based behavior" (Rasmussen, 1986), "procedural knowledge" (Anderson, 1982), and "associative skill" (Fitts & Posner, 1967). One fundamental challenge in designing effective DAI's is to provide dynamic changes in display or control information that do not interfere with either the development or the execution of skilled behavior. The results of the present experiment appear to indicate that this is possible.

A more extensive evaluation (with modification of the advanced control and display) will be required to solidify the preceding conclusions. However, the long-range goal of the research program is to demonstrate that dynamically adaptive interfaces can produce increments in performance, relative to a static interfaces that portray the same information. A fundamental step in this direction will require the development of a more rich experimental environment. The factors that drive the need for dynamically adaptive interfaces (a wealth of information, limited display real estate) are not currently present. Therefore, additional task requirements that are typically associated with low-level navigation (e.g., avoiding threats, delivering ordnance) should be incorporated. A complementary step will be the incorporation of more complex mechanisms to trigger adaptive changes on the part of the interface. Performance models will be difficult to implement, however there are several viable alternatives. Real-time assessments of workload are a possibility, and are consistent with on-going projects within the branch. A second possibility is to exploit Rouse's notion of leading indicators. For example, micro-analysis of control inputs should provide a reasonable indicator of workload and therefore a predictor of impending performance declines (and the need for adaptive behavior).

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Appendix A

The computational aiding portion of the CFD HUD display was based on the B1 bomber navigation system, as described in Marshall (1983). The equations and portions of the following descriptions are taken directly from that publication.

The "centerline recovery" algorithm calculates the path back to the desired waypoint centerline in minimal time. The base equation is $\phi_c = K_\psi \psi_e + K_Y Y_e$, where ϕ_c is the directed bank angle for the pilot, ψ_e is the error between the aircraft heading and the waypoint centerline heading, Y_e is the horizontal error from the waypoint centerline, K_ψ is an arbitrary gain value (3.0) for heading error, and K_Y is an arbitrary gain value (0.0005) for position error (the gain values corresponded to angular errors measured in degrees and positional errors measured in feet). The first term ($K_\psi \psi_e$) can be thought of as heading correction, and the second term ($K_Y Y_e$) as position correction. The heading correction attempts to direct the aircraft parallel to the waypoint centerline, while the position correction makes adjustments to intercept the centerline. As the aircraft gets closer and closer to the waypoint centerline, the position correction term approaches zero, and the aircraft eventually will fly parallel to the centerline. A similar equation was used for altitude deviation, replacing horizontal error with vertical error, and waypoint centerline with desired glide slope. The gain values were set considerably higher ($K_\psi = 1.0$ and $K_Y = 0.04$) for the vertical equations, since the mission involved low-level flight navigation, and altitude error was deemed to be more critical than horizontal error.

The "turn short" algorithm calculates a desired flight path for transitioning between waypoints. The algorithm produces a path that will keep the aircraft as close as possible to both waypoint centerlines during a waypoint transition, by starting the turn before the upcoming waypoint so that the aircraft turn path is tangent to the next waypoint centerline. The algorithm consisted of the following two equations: $R = V^2 / (G * \tan 60)$ and $D = R \tan (Y / 2) + 4V$. "Y" is the heading change from the current waypoint centerline to the next waypoint centerline, "V" is the ground speed of aircraft (feet/sec), and "G" is the acceleration of gravity (feet/sec^2). "R" is calculated as the turning radius of the aircraft based upon a bank angle of 60 degrees, and "D" is the calculated turn short distance. Thus, the turn short distance is calculated based on the aircraft speed, desired bank angle, and the heading difference between the two waypoint centerlines. If the aircraft is closer than the turn short distance to the upcoming waypoint, then waypoint sequencing occurs and the pilot will be directed to begin turning.

The "90-degree test" algorithm serves as a backup waypoint sequencing method, if the aircraft is never closer to the upcoming waypoint than the turn short distance. In this case, the heading from the aircraft to the next waypoint is compared to the heading of the current waypoint centerline. If the difference is more than 90 degrees, waypoint sequencing occurs. The 90-degree test used the following logic: h = abs (Hc - Ha); if h > 180, h = 360 - h, else if h > 90, sequence to next waypoint. "Hc" is the current waypoint centerline heading (in degrees), and "Ha" is the heading from the aircraft to the upcoming waypoint (in degrees).

The "delta-limit filter" algorithm ensured a quick response time of the flight director output, but at the same time prevented the output from changing drastically within a very short time. When waypoint sequencing occurred, the flight director output could instantaneously change to drastically different angles, which might be disorienting to the pilot, especially if it takes the pilot a moment to relocate the flight director on the HUD. The delta-limit filter compares the directed angles at each update of the HUD with the directed angles at the last update. If the change (delta) is too large, it limits the displayed change to a maximum value. This method allows small changes to appear immediately, but forces larger changes to take several seconds to fully develop. The maximum change per HUD update was 0.5 degrees for the bank angle and 0.1 degrees for the pitch angle, which (at a 15 Hz update rate) results in a maximum change per second of 7.5 degrees and 1.5 degrees for the bank angle and pitch angle, respectively. Though less intuitive, the maximum change per second of the speed box of the CFD was .075, which represents a timing error of 3.375 seconds.